DESIGN & CONSTRUCTION OF INCHEON BRIDGE CSB PYLON

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1. INTRODUCTION

The pylons of the cable-stayed bridge of Incheon Bridge are located in the main navigational channel of Incheon Harbour within the 12.3km marine section of Incheon Bridge. The reversed Y-shape of the pylons has a height of 238.5m. The major features examined for the reaction of the pylon structures are the control of the profile and verticality (1/2000) of the piers, the placing of in highly elevated concrete including the placing of mass concrete, the control of

cracks in vulnerable portions, the selection and operation of forms in the tapered and inclined structures, the construction of the struts of the pylons and the construction of the cable anchorages. This paper intends to present the relevant technologies applied to date in the construction process of the pylons of the cable-stayed bridge of Incheon Bridge.

2. APPLICATION OF GEOMETRY CONTROL PLANNING

The erection of the pylons was executed so as to achieve agreement between the measured profile and target values according to the planned geometry of the pylons. The planned geometry was obtained by means of the camber calculation considering the elastic deformation, creep and drying shrinkage of concrete according to the age of concrete at each erection stage of the pylons. Figure 1 shows the geometry control diagram of the pylons as a graph plotting the error between the planned geometry and the actual erected profile. A total of 6 items were examined for the geometry control. These are the transverse and longitudinal displacements of the pylon shaft, the twist of the shaft, the height of the pylon, the horizontal members and the measured temperature. The measuring frequency of the forms in each lot is 1 time prior to placing and 2 times after placing.
Peak measurement was conducted for the deformation of major points to evaluate continuously the geometry of the completed system according to the erection stage of the pylon shaft. Peak measurement was carried out at 6 positions that are the base of pylon shaft, the horizontal member, the position of the strut and the connection of the pylon (top of lot 43) as shown in figure 2. Targets were installed at each peak measurement position and measurement was executed after completion of each major erection stage. The camber of each erected structure in each lot was computed through camber analysis. Since the execution of the camber in each lot was difficult in terms of constructability, the positions at which camber could be omitted were evaluated by implementing the camber once in lot 1 so as to establish the camber planning.

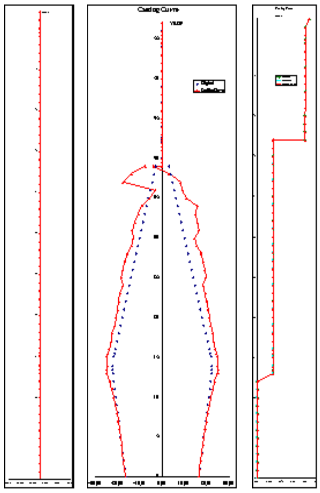


Figure 1: Geometry control diagram of the pylons of the cable-stayed bridge.

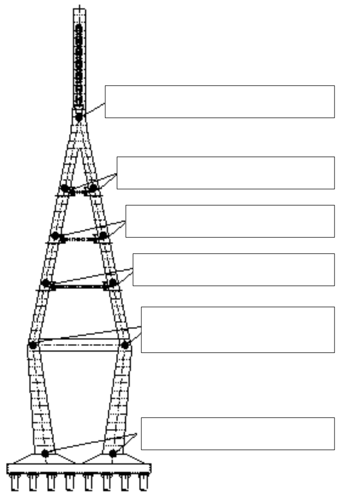
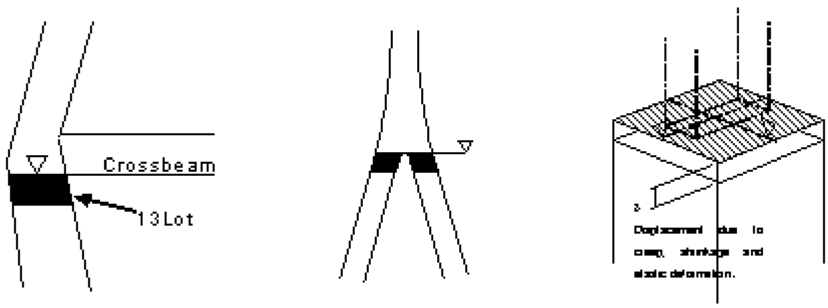


Figure 2: Positions of peak measurement.

2.1 Vertical Direction

The vertical camber is applied in the 3 positions shown in figure 3: the connection of the struts, the connection of the 2 shafts and the shield connection.



Strut connection (camber: 26mm) | 2-shaft connection (camber: 79mm) | Shield connection (camber: 80mm)

Figure 3: Positions applied with vertical camber.

2.2 Horizontal Direction

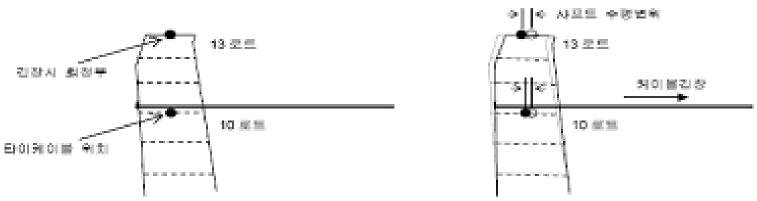
In the horizontal direction, the camber was calibrated according to the values computed for the transverse direction. The camber was computed and managed for each lot. Table 1 lists the camber for major parts of the geometry control during the erection of the pylons.

Table 1: Transversal camber.

	36N	36S	37S	38S	39S	37N	38N	39N
Camber (mm)	+14	+23	+24	–4	–47	–88	–67	–30

2.3 Introduction of Axial Force in Temporary Strut and Temporary Tie

A tension T = 2,000kN was applied in the temporary tie during the erection of the lower part. This force being was applied to reduce the bending moment of the cantilevered pylon and was not used for the displacement control in the erection. According to the pylon's geometry control plan, a pipe was embedded in lot 10 for the tie cable and the design axial force was applied after completion of the placing and curing of the lot 13 pylon. During the introduction of the axial force, the displacement at the position of the tie cable was 14mm and the displacement at the top of lot 13 was 15mm.



Fixing of tie cable

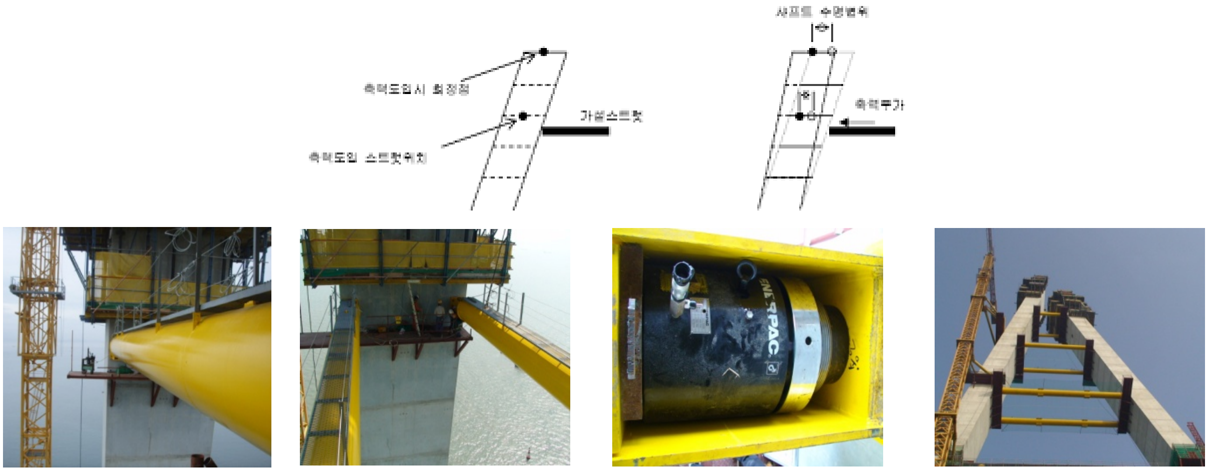
Completion of fixing

Tensioning

Completion of tensioning

Figure 4: Introduction of axial force in temporary tie.

A tension T = 2,000kN was applied in the temporary strut during the erection of the middle part. The temporary strut was installed for the same objective of the temporary tie.



Fixing of strut | Completion of fixing | Introduction of axial force | Completion of tensioning

Figure 5: Introduction of axial force in temporary strut.

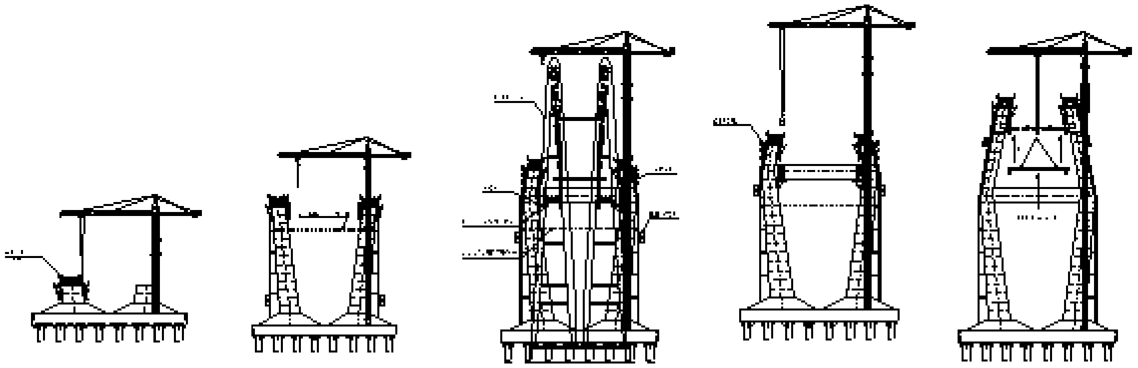
The displacements of the struts and pylon during the introduction of the axial force are listed in Table 2.

Table 2: Displacements of the struts and pylon according to the introduction of axial force in the temporary strut.

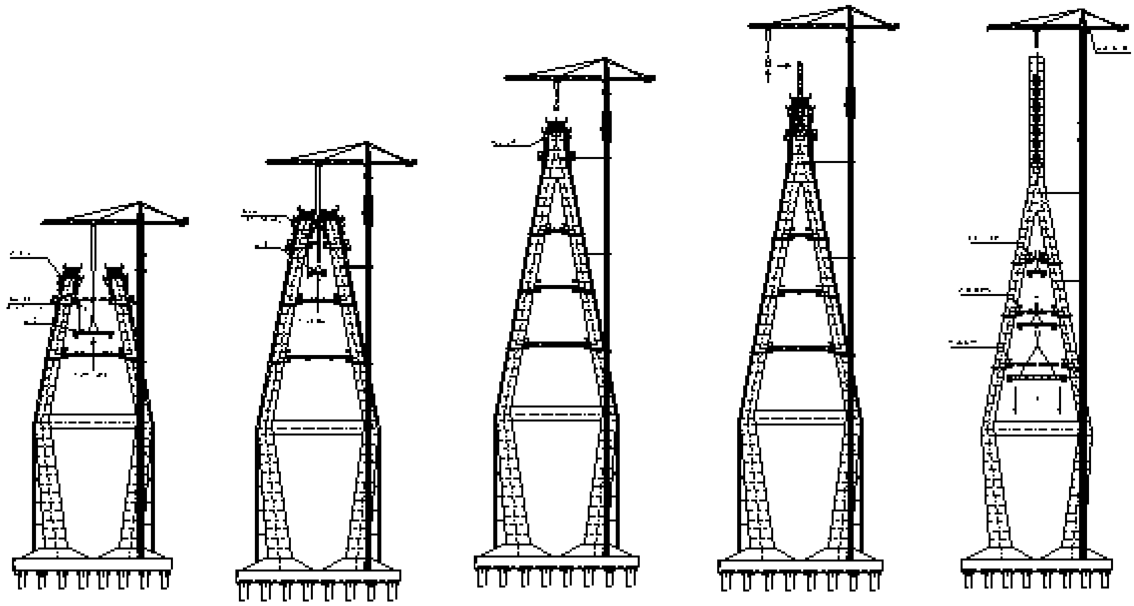
	Position of strut with axial force	Displacement of top during introduction of axial force (2 lots higher than the strut)	Introduced axial force	Maximum axial force (temperature considered)
1st strut jacking	10mm	13mm	F = 2,000kN	F_{max} = 5,730kN
2nd strut jacking	15mm	20mm	F = 2,000kN	F_{max} = 5,560kN
3rd strut jacking	16mm	21mm	F = 2,000kN	F_{max} = 6,210kN

2.4 Correction of Pylon's Planned Coordinates According to Modification of Erection Sequence

Figure 6 describes the erection sequence of the pylons of the cable-stayed bridge.



ACS setting | Installation of temporary tie | Installation of horizontal member | ACS setting | 1st strut (lot 22)



2nd strut (lot 28) | 3rd strut (lot 34) | ACS setting | Installation of shield block | Completed pylon

Figure 6: Erection sequence of pylon.

The interference between the 3rd strut and ACS form would be inevitable in case of the execution of the original planning. Accordingly, a practicable construction method was conceived and the geometry control plan was modified.

Original schedule: 36N → 36S → 37S → 38S → installation of 3rd strut → 39S → 37N → 38N → 39N

Modified schedule: 36N → 36S → installation of 3rd strut → 37S → 38S → 39S → 37N → 38N → 39N

(N: north side, S: south side)

Placing of lot 36S and 36N

Installation of 3rd strut

Working on lots 37S, 38S, 39S,
Stand-by in lot 36N

Stand-by in lot 39S,
Working on lots 37N, 38N, 39N

Connection of pylon,
erection of lot 40

First erection of trestle

Figure 6: Erection sequence of pylon.

3. ESTABLISHMENT AND APPLICATION OF CRACK CONTROL PLANNING

Planning for the crack control has been established in order to control early cracks in section previewed to experience cracking during the erection of the pylons. This planning included the analysis, monitoring and erection methods. The sections in which the application of the hydration heat analysis results were required are (1) the pilecap and pedestal, (2) the base of pylon shaft, (3) the connections of the pylon struts, and (4) the closure of the pylon. Figure 23 illustrates the shape of the model necessary for hydration heat analysis. The erection method was decided based on the examination of the optimal solutions for each section.

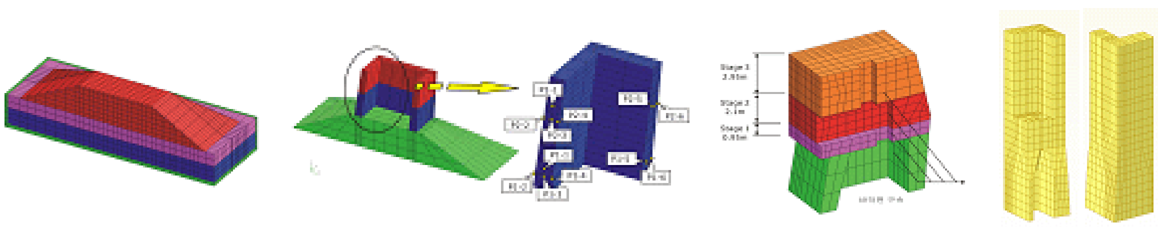


Figure 7: Shape of the model required for hydration heat analysis.

3.1 Pilecap and Pedestal

The erection sequence of the pilecap is as follows:

(1) Three-component cement is used as material for the construction of the pilecap.

(2) The laitance is removed after completion of the placing of one segment (2.7m).

(3) Surface polishing is executed after five days of curing in fresh water (50mm) followed by the placing of the second segment (2.1m).

(4) The laitance is removed and curing in fresh water is conducted during 7 days.

Figure 8: Placing of pilecap.

The erection sequence of the pedestal is as follows:

(1) After the surface polishing, cooling pipes are installed at spacing of 800mm at the upper, lower, left and right together with the arrangement of rebars. The pedestal is then placed 30 days after curing in fresh water. During placing, expanded polystyrol (EPS, 50mm) and curing cloth are disposed on the surface of the form to secure insulation curing.

(2) Cooling water is circulated at speed of 0.6m/sec and introduced at temperature of 15°C during 7 days. If the difference of temperature of water drops below 3°C between the entry and exit, cooling is interrupted even before the end of the period of 7 days.

(3) The surface at the top of the pedestal is cured with fresh water during the pipe cooling period (7 days) and the forms are removed after 10 days.

Figure 9: Placing of pedestal.

3.2 Base of Pylon Shaft

The erection sequence of the pylon shaft base is as follows:

(1)Execution of the surface polishing of the pedestal and arrangement of rebars.

(2) Placing 4.0m of lot 1 with plywood forms.

(3) Removal of forms 2 days after placing.

(4) Placing of 2nd stage 4 days after removal of forms.

(5) Erection at repeated cycles of 6 days.

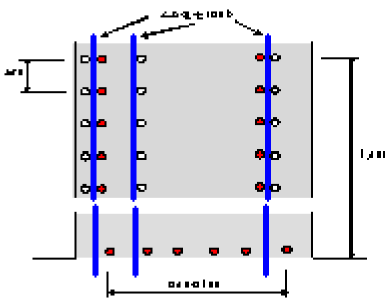


Figure 10: Supplemental rebars for the control of thermal cracks.

For the middle portion of the wall, the occurrence of cracks caused by external restraints has been already observed in numerous examples. Therefore, apart from the above mentioned methods, additional measures were applied to reduce the risk of cracking.

(1) As shown in figure 10, the additional rebars (●) are installed from the bottom of the wall to a height of 1.25m and D25 rebars are disposed at the bottom at spacing of 150mm.

(2) Cooling is executed so as to maintain the placing temperature below 23°C.

(3) After stripping of the forms up to the 2nd level, a curing cloth or vinyl is disposed on the surface to minimize drying shrinkage of the surface due to wind and sunlight.

(4) In case of occurrence of cracks, repair shall be executed in compliance with the crack repair procedure previously submitted.

Arrangement of additional rebars

Placing of concrete

Application of surface curing agent

Figure 11: Placing of concrete of the pylon shaft base.

3.3 Connections of Pylon Struts

Hydration heat analysis was conducted for the early cracks that might occur during the erection of the pylons of the cable-stayed bridge of Incheon Bridge and the corresponding erection methods were examined. The examination of the optimal solutions for the pylon's base made it possible to derive the following conclusions.

- Since works are performed in winter, hot-wires are installed on the external forms and insulation on the internal forms considering the drop of the temperature below 0. And, construction is conducted by disposing vinyl and curing cloth of the placed surfaces after stripping.

Figure 12: Protection of concrete in winter.

• Placing is executed to a height of 0.95m for lot 14-1, 2.05m for lot 14-2, and 3.20m for lot 15. One erection cycle extends over a period of 15 days, with the forms maintained during a period longer than 6 days. The temperature of the surface of concrete is maintained beyond 10°C during a period longer than 5 days after stripping.
• The following arrangement of reinforcement is done to secure additional stability:
- Disposition of horizontal D13@150 rebars over the whole section as internal and external thermal rebars for the box of the pylon;
- Extension of the length of the half of the reinforcement bars of the pylon’s opening to be inserted inside the wall;
- Additional horizontal arrangement of D22@300 on the whole height of lot 14-2.

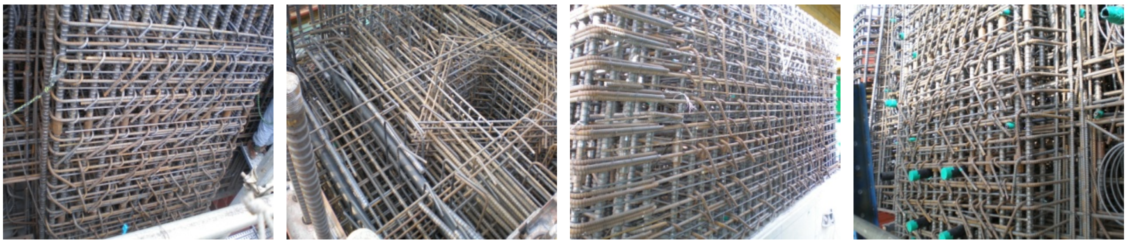


Figure 13: Arrangement of additional reinforcement.

3.4 Closure of Pylon

Based on the examination of the analysis and erection method results, curing was performed according to Table 3 to minimize the occurrence of cracking.

Table 3: Curing time-schedule of the closure of pylon

Position	Maintaining period of forms	Installation of insulation after stripping	Subtotal
45-1	2 days	6 days	8 days
45-2	2 days	3 days	5 days
After 46	2 days	–	2 days

4. CONCRETE PLACING BY PUMPING

The first placing of the pylon's concrete is performed by direct placing using a pump car until the lot enabling placing by floating B.P (lots 1~5). Sections where direct placing is impossible were planned to be placed using a floating B.P and high-pressure pump. The following items needed to be examined for the placing by pumping: (1) modification of the mix design, (2) computation of the pump pressure during placing, (3) selection of high-pressure pump, (4) fixation method of piping in placed section, and (5) maintenance and inspection method of high-pressure piping system.

4.1 Modification of Mix Design

For the pumping of the higher part, the loss of pressure varies according to the mix characteristics like the design strength and fluidity. The pumping pressure decreases with higher fluidity. Since the standards of the concrete applied to the pylon ate 20-45-18, the improvement of the fluidity (workability) was required for the pumping of the high part. Especially, the quantity of binder for concrete being 500kg/m^3, which is larger than ordinary strength concrete, the relative viscosity of concrete augmented and increased the hydraulic pressure and pressure of concrete during the pumping. Accordingly, the fluidity of concrete needed to be adjusted upward to improve the pumping performance. Even if the slump constitutes a reference for the fluidity when high strength concrete is placed horizontally or downward, it is advantageous to increase the fluidity as possible when placing upward.

In case where upward placing is performed with low fluidity, the hydraulic pressure of the pump and concrete increase, which may reduce the exhausted quantities or obstruct the pipe. Table 4 presents the modified design mix applied for the pylons of the cable-stayed bridge of Incheon Bridge.

Table 4: Mix design (45MPa) of pylon.

Mix design	W/B (%)	S/a (%)	Volumetric quantities (kg/m^3)					
			Water	Cement	Slag	S	G	Ad
Original	32	42	160	250	250	681	956	4.5
Modified	32	46	160	250	250	753	911	8.0

4.2 Computation of Pump Pressure during Placing

A pipe line of 246m of which 20m horizontally and 226m vertically is required until the top of the pylon. Table 5 summarizes the required pressure computed for each section.

Table 5: Pressure required for pumping placing of pylon.

Item		Unit	Quantity	Pressure
Initial pressure		20bar/shaft	–	20bar
Pipe	Vertical pipe (3m/pipe)	1bar/4m	75	57
	Horizontal pipe (3m/pipe)	1bar/20m	6	1
	90° curved pipe	1bar/1ea	3	3
	45° curved pipe	1bar/2ea	4	2
	Other curved pipes	1bar/10ea	4	1
Pipe coupling		1bar/10ea	92	10
Coefficient of friction		20%	–	19
C.P.B		15bar	–	–
End hose		2bar	1	2
Total				115
Safety factor		10%	–	12
Total pressure				127
Actual coefficient		30%	–	38
Actual pressure				**165**

4.3 Selection of High Pressure Pump

The selection of the equipment was done as examined above with focus on (1) the possibility to secure placing with pressure larger than 165bar considering the horizontal and vertical lengths of the pipes, and (2) the possibility to exhaust the adequate quantity of concrete (50m^3/hr) at high pressure. Four devices were examined of which 2 were judged to be appropriate as shown in Table 6.

Among these devices, BP 8000HDR of Schwing has been selected considering the efficiency on site. This equipment is identical to that used in the site of the 1st and 3rd complexes of Tower Palace in Seoul, which recorded experience in direct pumping of more than 250m. Therefore, its use for the 238.5m of the pylon appeared to be sufficient.

Table 6: Comparison of high-pressure pumps

Item	Circulator pump	High pressure pump (Schwing & Putzmeister)		
	BSA2110H-D	BP 4000HDR	BSA2110HP-D	BP 8000HDR

Capacity	Max. pressure (bar)	160	201	220	201
	Exhaust (m^3/hr)	69/103	43/66	76/110	55/87
Comparison	> 150bar	O	O	O	O
	> 50m^3/hr	O	X	O	O
	Judgment	X	X	O	O

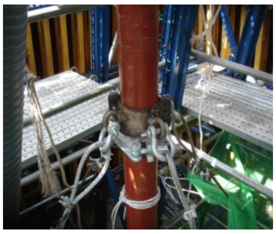
4.4 Fixation Method of Piping System in Placed Section

Piping should be done until the constructed part to perform pumping placing. In structures like common high-rise buildings, the concrete piping works can be executed easily by using the slabs of the lower floors. However, for vertical and hollowed structures like the pylon, piping constitutes a difficult problem. A survey of the research dedicated to the installation of concrete pumping pipes in ACS system was done but this survey led to the conclusion that safety problems would occur due to the loads and vibrations accompanying placing. Accordingly, support platforms were installed so as to enable the installation inside the pylon and the connection of the concrete pumping pipes. The supporting platform is equipped with anchors at both ends, a lower support fixing and supporting the concrete pumping pipe curved toward the center inside the pylons, an upper support supporting the pipe re-curved from the center to the placing position inside the pylon, and a connecting member linking monolithically the lower and upper supports. This system has been licensed as the “supporting platform of concrete pumping pipe and construction method of cable-stayed bridge pylon using this supporting platform” (license No. 10-2007-0027669).

Installed support platform

Wall support

Upper end of piping



Fixing equipment for pipes

Figure 14: Fixation system of placing piping.

5. ACS FORM METHOD

The pylons of the cable-stayed bridge of Incheon Bridge have a height of 238.5m, which make them highly elevated piers with continuously varying cross-section and slope. These pylons are also influenced by winds due to their topographical position. Therefore, need was to examine carefully the selection of forms. Table 7 compares the advantages and disadvantages of the ACS form and slip form generally adopted for the erection of highly elevated piers.

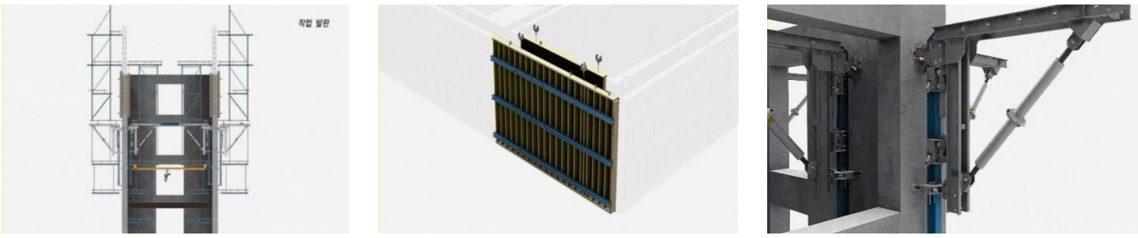
Table 7: Comparative analysis of ACS form and slip form

Item	Auto Climbing System Form	Slip Form
Productivity	• Number of forms required: 1 set per pylon (1 device for each north and south sides) • Cycle time: 6 days per lot (net-day excluding the modification period of the form)	• Number of forms required: 1 set per pylon (1 device for each north and south sides) • Cycle time: 1.2m/day (net-day excluding the modification period of the form, bad weather and interruption of slip up)
Average working time	• Possibility to work 24 hours continuously	• Possibility to work 24 hours continuously
Constructability	• Long time required for finishing during erection due to large number of accessories • Need of curing period for each lot and relatively longer erection time	• Imperative need of skilled manpower for continuous working • Need of long time for construction joints and preparation of forms during interruption of works due to external causes like bad weather
Quality control	• No need for particular care on mix when grade management is done with respect to the design concrete mix • Ease of quality control of concrete and small material loss • Ease of surface curing and smooth surface	• Need to control slip up speed due to diminution of admixtures according to changes of weather and embedded matters • Difficult quality control in case of rainfall during continuous work • Poor surface finishing and high risk of horizontal cracks or plastic cracks
Selection	O	X
Reason for selection	• In the case of slip form, occurrence of delays and work interruption due to evacuation of equipment during bad weather • In the case of slip form, need for larger number of B/P due to thee continuous use of floating B/P	

5.1 Composition of ACS

The ACS is composed by a working platform, the forms and jacking devices as shown in figure 15.

Working platform	Form	Jacking device



Provision of work space	Form for concrete placing	Device enabling self climbing

Figure 15: Composition of ACS.

5.2 Cross-sectional Shape of ACS Form

The pylon is subdivided into the lower part, cross-beam part, middle part and upper part according to the construction stages. The shapes of the ACS by part are illustrated in figure 16.

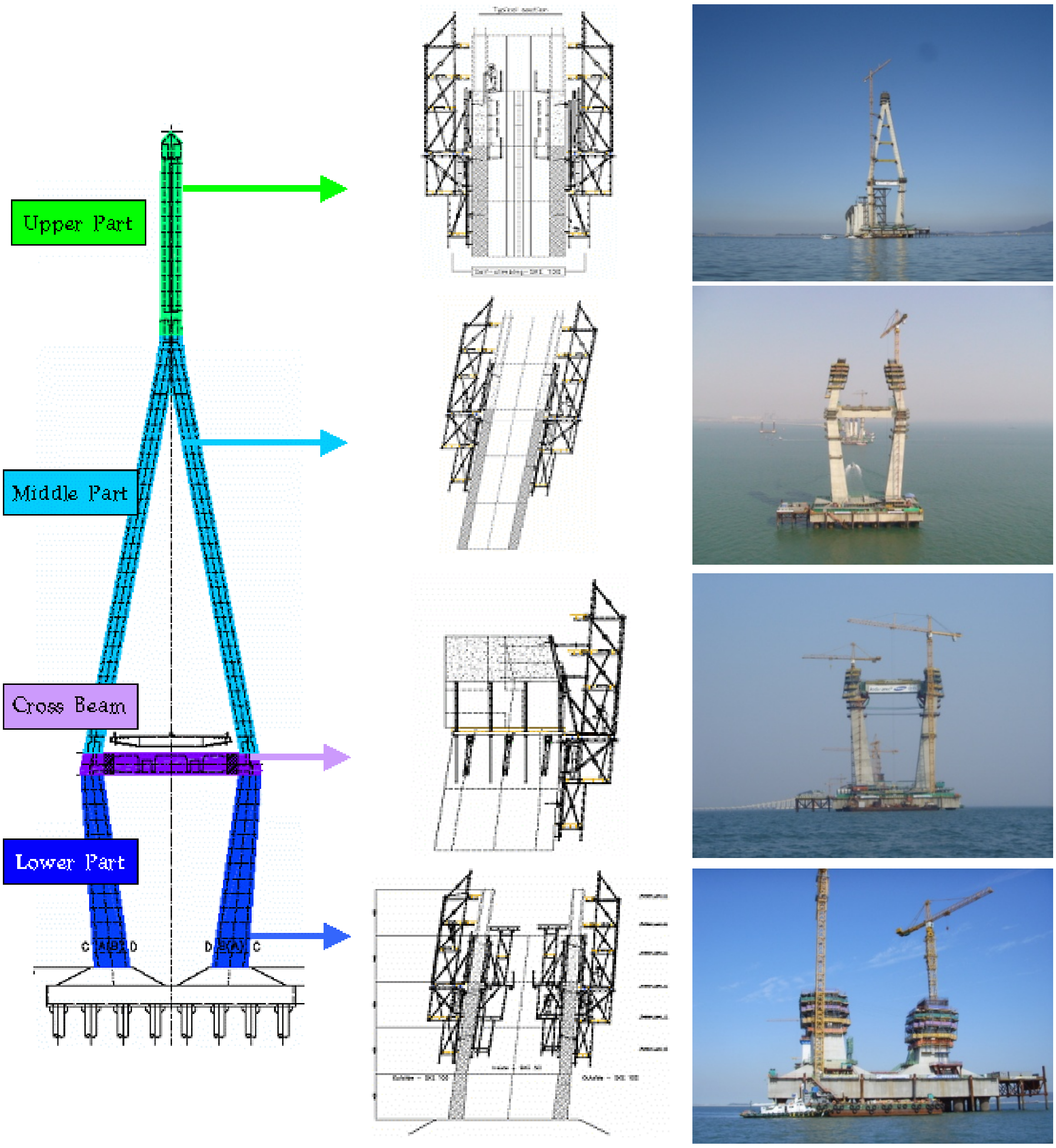


Figure 16: Cross-sectional shapes of ACS form.

6. PRECAST OF PYLON'S CROSS BEAM

The two cross-beams (6×6×31.6m) connecting lots 14 and 15 among the 57 lots of the pylons of the cable-stayed bridge have been pre-casted in the onshore workshop. The precast cross-beams were then hauled to the site (W1, E1) using a 3000ton floating crane. Once on site, the beams were disposed at the top of the brackets installed on the pylons and the connections were cast-in-place (2.7m×2) so as to be monolithically linked to the pylon and be installed with the bearings of the stiffening girder. This process allowed significant shortening of the construction period.

Table 8: Comparison of the work schedules of Seohae Bridge and Incheon Bridge

Seohae Bridge: Fabrication of half sections and pulling by hydraulic jack									
Work schedule	1	2	3	4	5	6	7	8	Period
1. PC fabrication of half section (onshore)									90 days
2. Installation of pulling equipment and cross-beams									27 days
3. Placing of pylon connections									50 days
4. Erection of upper slab									60 days
Interference with pylon's works									227 days
Incheon Bridge: Unified fabrication and FC erection									
Work schedule	1	2	3	4	5	6	7	8	Period
1. PC fabrication of whole cross-beam (onshore)									90 days
2. Installation of brackets and cross-beams									20 days
3. Placing of connections and tensioning of tendons									22 days
Interference with pylon's works									132 days

As shown in Table 8, the unified erection of the cross-beams enabled a shortening of the construction period by 95 days. This solution also minimized the interference period with the pylons' works and enabled to secure the progress of the works.

The works processed by the entry of the floating crane in the workshop followed by the fastening of the fixation and wires. After the hauling of the cross-beams, the convoy moved to the site. The cross-beams were then disposed at first on the top of the hydraulic jacks. At that time, the monitoring team waiting at the top implemented minute adjustments based on the measurements and the installation was completed. The installation error was ±20mm in the longitudinal direction, ±30mm in the transverse direction, and ±20mm for the elevation.


Entrance in workshop


Fastening of fixation


Hauling of cross-beam


Transport to site


Approach to pylon


Pulling of cross-beam


Installation of cross-beam


Evacuation of F/C

Figure 17: Installation of cross-beams.

7. CONSTRUCTION ACHIEVEMENTS

7.1 Work Progress

Table 9 compares the actual working days for the erection of the pylons compared to the planned schedule.

Table 9: Actual working days for the erection of the pylons vs. planned schedule

	Planned (days)	Actual (days)	Remarks
Pilecap	42	56	
Pedestal	31	23	
Pylon lower part	105	166	Cycle: 11 days/lot
Cross-beam	24	29	Installation of bracket and cross-beams: 20 days Placing of connections and tensioning of tendons: 22 days
Pylon middle part	222	114	Cycle: 4 days/lot

※ The number of days corresponds to the net-working days. The upper part of the pylon is currently under construction

7.2 Geometry

Figure 18 presents the geometry control diagram until the current erection schedule. The maximum construction error in the transverse direction is 18mm for 34N at W1 and 20mmm for 9S at E1.

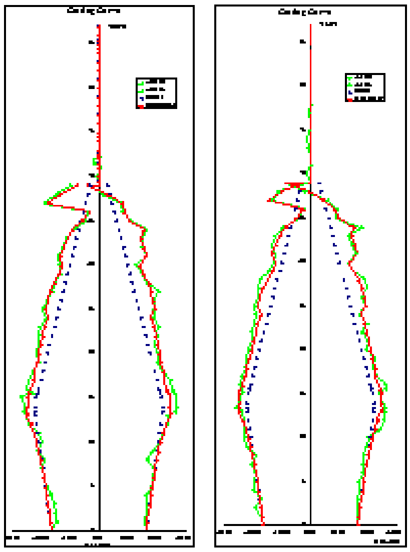


Figure 18: Geometry control diagram of the pylons at W1 and E1.

8. CONCLUSIONS

Since the Incheon Bridge project is implemented through the fast track method in which construction and design are conducted simultaneously, the detail design has been provided by reflecting the constructability throughout close cooperation between the design team and construction team. Apart from the features presented above, significant cost reduction and quality control of the structure have been realized by the introduction of the 6-Sigma methodology, which enabled improvement of the rebar assembly method, operation of ACS forms, placing of concrete, and efficiency of the management of equipment. For the remaining and future process, the inefficient factors impeding the execution of the works will be removed through thorough investigation and preliminary surveys so as to contribute to the advancement of the domestic offshore construction technology.